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Brittle deformation along the Gulf of Alaska margin in response to Paleocene-Eocene triple junction migration

Peter J. Haeussler
Dwight C. Bradley
U.S. Geological Survey, 4200 University Drive, Anchorage, Alaska 99508, USA

Richard J. Goldfarb
U.S. Geological Survey, Box 25046, MS 973, Denver Federal Center, Denver, Colorado 90225, USA

ABSTRACT

A spreading center was subducted diachronously along a 2200 km segment of what is now the Gulf of Alaska margin between 61 and 50 Ma, and left in its wake near-trench intrusions and high-*T*, low-*P* metamorphic rocks. Gold-quartz veins and dikes, linked to ridge subduction by geochronological and relative timing evidence, provide a record of brittle deformation during and after passage of the ridge. The gold-quartz veins are typically hosted by faults, and their regional extent indicates there was widespread deformation of the forearc above the slab window at the time of ridge subduction. Considerable variability in the strain pattern was associated with the slab window and the trailing plate. A diffuse network of dextral, sinistral, and normal faults hosted small lode-gold deposits (<50,000 oz) in south-central Alaska, whereas crustal-scale dextral faults in southeastern Alaska are spatially associated with large gold deposits (up to 800,000 oz).

We interpret the gold-quartz veins as having formed above an eastward-migrating slab window, where the forearc crust responded to the diminishing influence of the forward subducting plate, the increasing influence of the trailing plate, and the thermal pulse and decreased basal friction from the slab window. In addition, extensional deformation of the forearc resulted from the diverging motions of the two oceanic plates at the margins of the slab window. Factors that complicate interpretations of fault kinematics and near-trench dike orientations include a change in plate motions at ca. 52 Ma, northward translation of the accretionary complex, oroclinal bending of the south-central Alaska margin, and subduction of transform segments. We find the pattern of syn-ridge subduction faulting in southern Alaska is remarkably similar to brittle faults near the Chile triple junction and to earthquake focal mechanisms in the Woodlark basin—the two modern sites of ridge subduction. Therefore, extensional and strike-slip deformation above slab windows may be a common occurrence.

Keywords: Alaska, Gulf of Alaska, triple junction, Paleocene, Eocene, lode gold, mesothermal gold, ridge subduction, slab window

INTRODUCTION

Subduction of an oceanic spreading center, commonly known as ridge subduction, perturbs the overriding plate both thermally and mechanically (e.g., Delong and Fox, 1977). Two diverging oceanic plates will continue to separate even after they are subducted, but new oceanic crust no longer forms in the gap between them (e.g., Thorkelson, 1996). The overriding forearc thus comes into direct contact with hot, upwelling asthenosphere at a slab window, resulting in anomalous igneous

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and hydrothermal activity (Dickinson and Snyder, 1979). In the general case where a subducting ridge is neither parallel nor perpendicular to the subduction zone, ridge subduction will be diachronous along strike. During oblique ridge subduction, a trench-ridge-trench triple junction migrates along the convergent margin, accompanied by a change in the plate convergence vector, and presumably, by a change in deformation regime in the upper plate. Moreover, the subduction of any topographically high object—whether seismically active or aseismic—would be expected to disrupt the friction at the base of the accretionary complex and cause it to deform (see Davis et al., 1983).

In this paper, we examine the structural effects of an inferred early Tertiary ridge subduction event along the Pacific margin of Alaska. Four suites of geologic features, each of them linked by precise geochronology to subduction of an oceanic spreading center, might reveal something about the mechanics of ridge subduction: (1) plutons, (2) high-temperature, low-pressure metamorphic terranes, (3) dikes, and (4) gold-quartz mineralized faults. In this paper, we focus on the regional structural trends of the dikes and the gold-mineralized faults. Kusky et al. (this volume, Chapter 12), Sisson et al. (this volume, Chapter 13), and Groome et al. (this volume, Chapter 14) focus on the plutons along this belt. Large plutons complicate the regional structures as their intrusion probably led to local mechanical instability in the accretionary wedge, perhaps masking the regional stress and strain regime. The high-grade metamorphic rocks have been studied locally in considerable detail (Hudson and Plafker, 1982; Goldfarb et al., 1986; Pavlis and Sisson, 1995; Sisson et al., 1989; and Zumsteg et al., this volume, Chapter 11). Our data include the attitudes and kinematics of 681 dikes and 104 gold-quartz mineralized faults and joints, representing regions along a strike-length of 1400 km. Although the structures show broad similarities from one location to the next, they also reveal considerable along-strike variation in the structural response of the accretionary complex to ridge subduction.

Geologic and Tectonic Setting

The Mesozoic and early Cenozoic accretionary complex along Alaska's Pacific margin, referred to as the Chugach terrane or Chugach accretionary complex, stretches from Sanak Island in the southwest to Baranof Island in southeastern Alaska (Fig. 1). Three accreted rock units recognized on the basis of age, rock type, and structural style are germane to the present paper. From landward to seaward and from west to east: (1) The Uyak Complex (Connelly, 1978), McHugh Complex (Clark, 1973), and Kelp Bay Group (Decker, 1980) are mélanges consisting of an argillaceous matrix and more competent blocks of graywacke, greenstone, tuff, Triassic to middle Cretaceous chert, gabbro, plus rare ultramafic rocks and Permian limestone. (2) The Campanian-Maastrichtian Shumagin Formation (Moore, 1973), Kodiak Formation (Nilsen and Moore, 1979), Valdez Group (Nilsen and Zuffa, 1982), and Sitka Graywacke (Decker, 1980) consist of siliciclastic turbidites thought to have originated as trench-fill deposits derived from uplift of the Coast Plutonic Complex

Figure 1. Overview of the southern Alaska Mesozoic–early Cenozoic accretionary complex and areas discussed in the text. The distance (in kilometers) along strike from Sanak to Baranof Island is also shown. Note that all the units in the accretionary complex are lumped together (see Plafker et al., 1994, for more details). CMC—Chugach metamorphic complex, which is an anomalous tract of high-*T*, low-*P* metamorphism (Sisson et al., 1989).

in southeastern Alaska and western British Columbia (Nilsen and Zuffa, 1982; Plafker et al., 1994). Tholeiitic metabasalts are also found in the Valdez Group and its correlatives (Plafker et al., 1994). (3) The Paleocene–middle Eocene Ghost Rocks Formation (Moore et al., 1983) and Orca Group (Winkler, 1976; Helwig and Emmet, 1981) also consist of siliciclastic turbidites along with pillow lavas. These rock units were progressively accreted to the southern Alaskan margin, and all of the units have been deformed and underwent low-grade metamorphism. We use the term "south-central Alaska" to refer to the region of coastal southern Alaska—from Kodiak Island to the Yakutat area. We refer to the panhandle of Alaska as "southeastern Alaska."

The regional structural grain—defined by foliation in the mélange units and by bedding and cleavage in the more coherent units—roughly parallels the coastline of Alaska and sweeps around a ~90° bend in the Prince William Sound area. This bend defines the south-central Alaska orocline (see Fig. 1). Oroclinal bending has been proposed on the basis of structural and paleomagnetic evidence (Carey, 1955; Grantz, 1966; Coe et al., 1985, 1989; Bol and Gibbons, 1992; Bol and Roeske, 1993; Haeussler and Nelson, 1993), although it is not universally accepted (e.g., Csejtey, 1992). Bending is thought to have involved a ~45° to 90° counterclockwise rotation of southwestern Alaska about a vertical axis, some time between ca. 65 and ca. 35 Ma (Coe et al., 1985, 1989). Bol and Gibbons (1992) proposed that a 45° initial bend was further tightened during accretion of the Orca Group by dextral strike-slip faulting in eastern Prince William Sound, which was accompanied by northwest-directed thrust faulting in western Prince William Sound.

Paleomagnetic data from Kodiak Island and the Kenai Peninsula have been interpreted to show that, in the early Tertiary, the accretionary complex was located 13° to 25° to the south, off southern British Columbia or Oregon and Washington (Plumley et al., 1983; Coe et al., 1985; Bol et al., 1992). The rock types, isotopic composition, and age of the Orca and Valdez groups are also consistent with a provenance in the Coast Mountains of British Columbia or southeastern Alaska (Dumoulin, 1987; Plafker et al., 1994; Farmer et al., 1993). Thus, although the presence of the Late Cretaceous and early Tertiary parts of the accretionary complex has been linked with uplift of the Coast Mountains of southeastern Alaska and Canada, neither the exact location of the accretionary complex, nor its orientation with respect to the present margin of southern Alaska, are precisely known for early Tertiary time.

Post-cleavage, "late" faults are locally abundant in the accretionary complex (Byrne, 1984; Sample and Moore, 1987; Bradley and Kusky, 1990, 1992; Kusky et al., 1997). These faults cut mélange fabrics in the McHugh Complex and folds and cleavage in the Valdez Group. Near Anchorage, three fault sets have been identified (Bradley and Kusky, 1990; Kusky et al., 1997): (1) a conjugate set of reverse faults with strikes subparallel to the present-day Aleutian trench, (2) a conjugate set of vertical strike-slip faults, whose acute bisector is perpendicular to the Aleutian trench, and (3) a conjugate set of normal faults that strike perpendicular to the Aleutian trench. Kusky et al. (1997) suggested that fault sets 2 and 3 comprise an orthorhombic fault system that was active at the time of ridge subduction, based on similarities in structural style to dated gold-mineralized faults elsewhere in the accretionary complex rocks.

Evidence for Ridge Subduction beneath Southern Alaska

Six independent lines of evidence suggest a spreading ridge was subducted beneath Alaska's Pacific margin during early Tertiary time. (1) Global plate reconstructions require that a Kula-Farallon spreading center was subducted somewhere along the western margin of North America in Paleocene and Eocene time (Engebretson et al., 1985; Atwater, 1989). Unfortunately, not enough Kula plate marine magnetic anomalies have been preserved to reveal where the ridge intersected the continental margin. (2) A belt of near-trench intrusions along Alaska's Pacific margin has been interpreted as having formed during ridge subduction, and thus they mark the migrating site of the elusive trench-ridge-trench triple junction (Marshak and Karig, 1977; Hill et al., 1981; Helwig and Emmet, 1981; Moore et al., 1983; Bradley et al., 1993; Pavlis and Sisson, 1995; Harris et al., 1996). These intrusions, collectively referred to as the Sanak-Baranof belt (Hudson et al., 1979), extend for 2200 km from Sanak Island on the west to Baranof Island on the east (Fig. 1). They are located between 75 and 250 km seaward of the coeval early Tertiary magmatic arc. The largest intrusions are elongate granodiorite plutons, such as the 100 km long Kodiak batholith, and there are many smaller stocks and dike swarms. Petrogenetic modeling of Paleocene granitoids on Kodiak Island suggests interaction between a parent magma similar to MORB and anatectically melted turbidites (Hill et al., 1981). Similarly, Barker et al. (1992) explained the geochemistry and isotopic composition of granitoids in eastern Prince William Sound by invoking heat from a subducted spreading center to melt the base of the accretionary complex. Harris et al. (1996) concluded from geochemistry that there were two magma sources for felsic intrusions in the eastern Chugach Mountains: metasedimentary rocks from the accretionary complex and a mafic source, possibly mantle derived, which may have been underplated oceanic material. (3) Near-trench magmatism progressed from ca. 61 Ma in the west to ca. 50 Ma in the east (Fig. 2; see Bradley et al., 1993 and this volume, Chapter 1; Poole, 1996. (4) Ophiolites and mafic rocks within the accretionary complex have unusual characteristics consistent with a ridge subduction origin. Two ophiolites have pillow lavas interbedded with turbidites, suggesting proximity of a spreading center to a sediment source (Bol et al., 1992). One of these has been dated at 57 ± 1 Ma (U/Pb zircon; Nelson et al., 1989)—slightly older than nearby near-trench plutons. This date suggests a spreading center was close to the location of near-trench magmatism (see Fig. 3 in Bradley et al., 1993). Basalts from two ophiolites have the geochemical signature of sediment-contaminated MORB (Nelson and Nelson, 1993; Hill et al., 1981). (5) High-T and low-P metamorphism—opposite of what

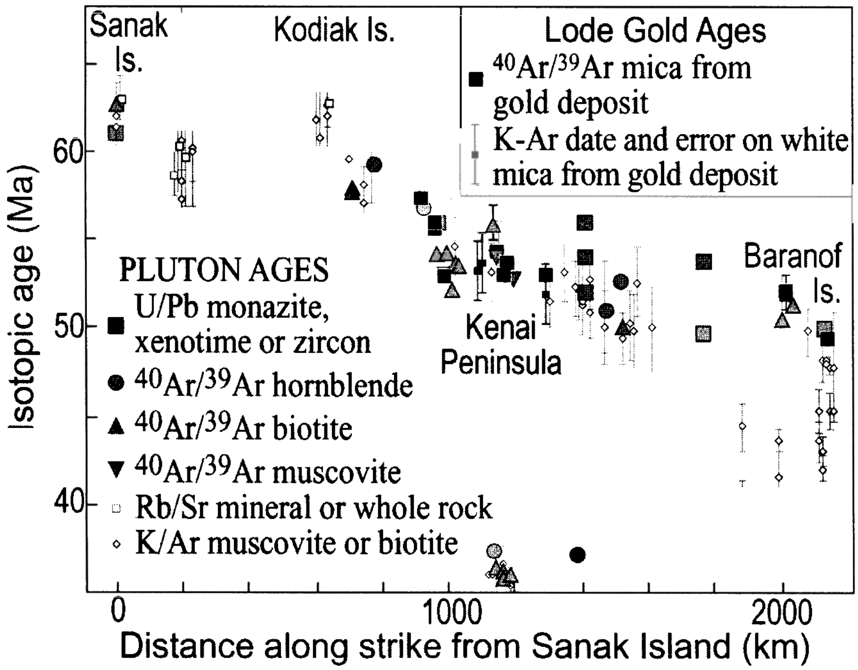


Figure 2. Age versus distance from Sanak Island of near-trench intrusions in the Sanak-Baranof belt. See Figure 1 for distance from Sanak Island. Note the large-scale diachronous trend in ages of older to the west and younger to the east, indicating a migrating trench-ridge-trench triple junction (Bradley et al., 1993). From Bradley et al. (2000).

is normally expected in an accretionary complex—occurred in south-central Alaska at the same time as nearby near-trench magmatism (see compilation of Bradley et al., 1993; Onstott et al., 1989). In the Chugach metamorphic complex, rocks in the accretionary complex were locally heated to temperatures of 650 °C at pressures of 2.5 kbar (Sisson et al., 1989; Pavlis and Sisson, 1995; Loney and Brew, 1987). An unusual heat source is required for these metamorphic conditions in an accretionary wedge setting. (6) The presence of abundant quartz veins, many containing gold, in fault zones and joints throughout the accretionary complex also supports a ridge-subduction interpretation. Temperatures of at least 300 to 400 °C are required for significant gold transport and large fluid volumes, both of which are compatible with a large heat pulse beneath the prism. This heat drove prograde metamorphic reactions with associated vein-forming fluid release at isograd reaction boundaries. The age of the veins decreases from west to east along the continental margin in a pattern similar to that shown by the near-trench intrusions (Haeussler et al., 1995; see Fig. 2). The mineralogy of the gold-bearing quartz veins and the temperatures and pressures of ore formation are fairly consistent over the entire area indicating a consistent regional process of gold mineralization (Goldfarb et al., 1986; Borden et al., 1992; Taylor et al., 1994).

We view the evidence for ridge subduction, slab window magmatism, and lode-gold deposition as compelling.

DISTRICT-BY-DISTRICT DIKE AND FAULT DATA

In this section, we focus on regional structural data for the dikes and the gold-mineralized faults (Fig. 3). Some of the dike orientation data are from our own measurements (principally in the lower Kenai Peninsula), some are from our compilation of structural data at gold occurrences, and the rest are from published geologic maps (see Fig. 3 caption for data sources). The dikes are commonly subvertical, and thus we present the data as rose diagrams of dike strike, which allows us to include dike orientation data from published maps (Fig. 3E).

Fault zones have been studied in greatest detail in areas of lode-gold mines and prospects found throughout much of the south-central Alaska accretionary complex (Fig. 1). We compiled published structural data from gold mines and prospects (Haeussler and Bradley, 1993), and synthesized this with our own data collected both from gold districts and elsewhere along the prism. The strength of the published data is that it covers a very broad region, from Kodiak to Baranof Island, and there are some structural measurements available from most mines and prospects, many of which are now inaccessible or unlocatable. We used reports from the early part of this century principally to determine if a gold-quartz vein occupies a fault zone, its orientation and dimensions, and any crosscutting relations (Haeussler and Bradley, 1993). Unfortunately, most of the published data are vintage 1910–1935, and they lack information on the sense of offset of faults.

In order to address this lack of kinematic data, we collected such information from 22 mines, prospects, or mineral occurrences. We then discarded old data that were vague or inconsistent and compiled all the new and old structural and kinematic data giving information on a total of 361 mines, prospects, and mineral occurrences in nine regions (Fig. 1; stereonets on Fig. 3). In the following sections we abstract the most important structural

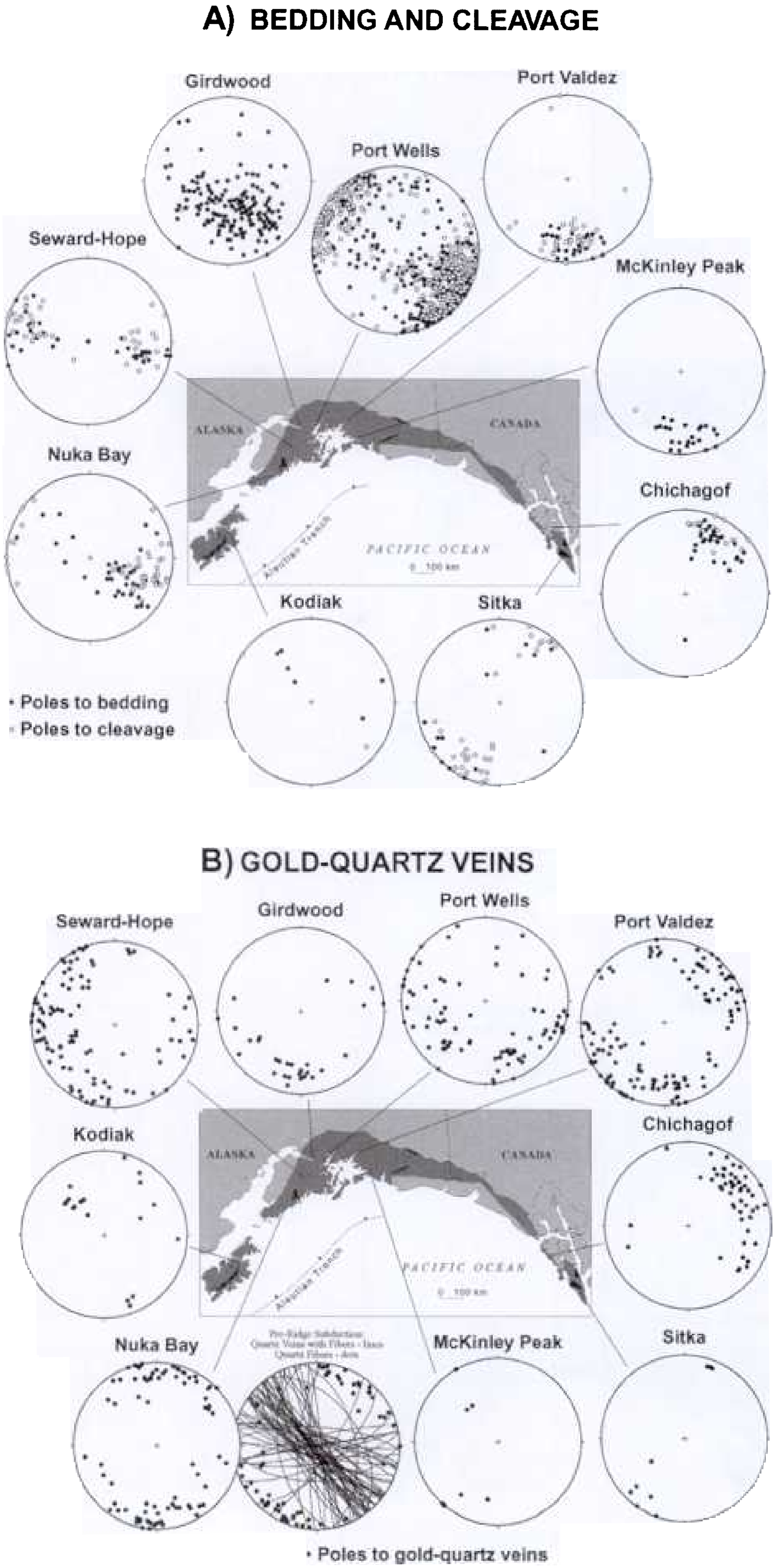
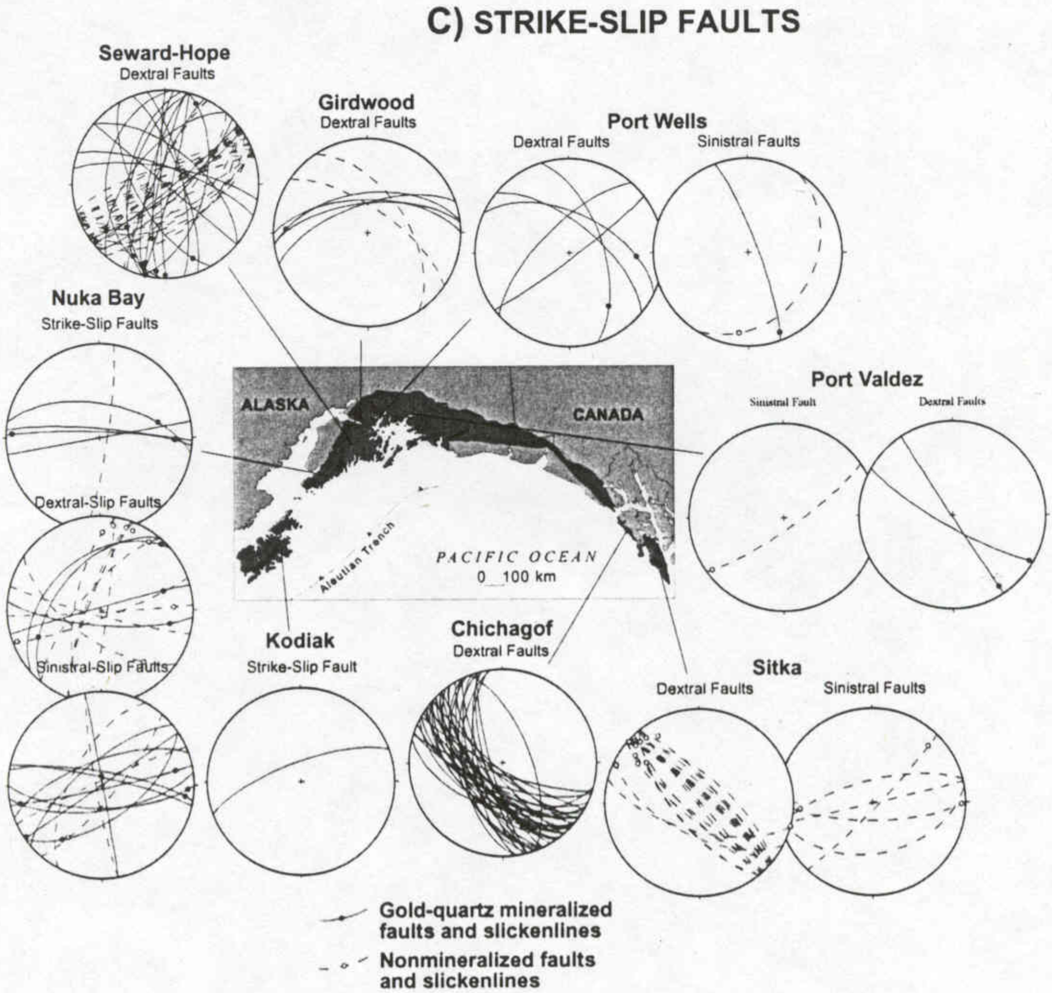
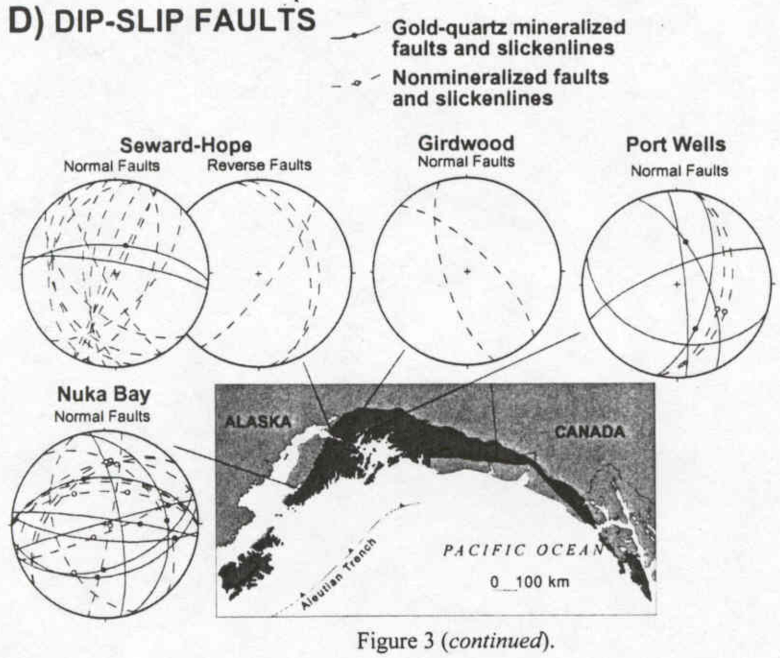


Figure 3 (*on this and following two pages*). Equal-area stereonet plots of structural data from regions of gold mineralization in the southern and southeastern Alaska accretionary complex. The index map has the same legend as Fig. 1. Data for the gold-bearing quartz veins and host faults come from our fieldwork and the 31 sources listed in the compilation of Haeussler and Bradley (1993). Data from southeastern Alaska come from Becker (1898), Wright and Wright (1905), Knopf (1912), and Reed and Coats (1941). Data on dike orientations come from the previously listed sources and Park (1933), Winkler (1992), and Plafker et al. (1992). A: Poles to bedding and cleavage. B: Poles to gold-quartz veins with additional plot of Nuka Bay area pre-Sanak-Baranof belt gold-quartz veins plotted as great circles and quartz fibers as dots. C: Gold-quartz mineralized strike-slip faults and slickenlines plotted on solid great circles, and nonmineralized faults and slickenlines plotted on dashed circles. D: Gold-quartz mineralized dip-slip faults and slickenlines plotted on solid great circles, and nonmineralized faults and slickenlines plotted on dashed circles. E: Rose diagrams of Sanak-Baranof belt dike strikes. Each petal has a 10° width, n is the number of samples plotted, and "longest" is the number of samples in the longest petal. F: Same data as in Figure 3E but rotated into a possible pre-oroclinal bending configuration. See text for discussion. Amount of clockwise rotation for each area is listed below each rose diagram.





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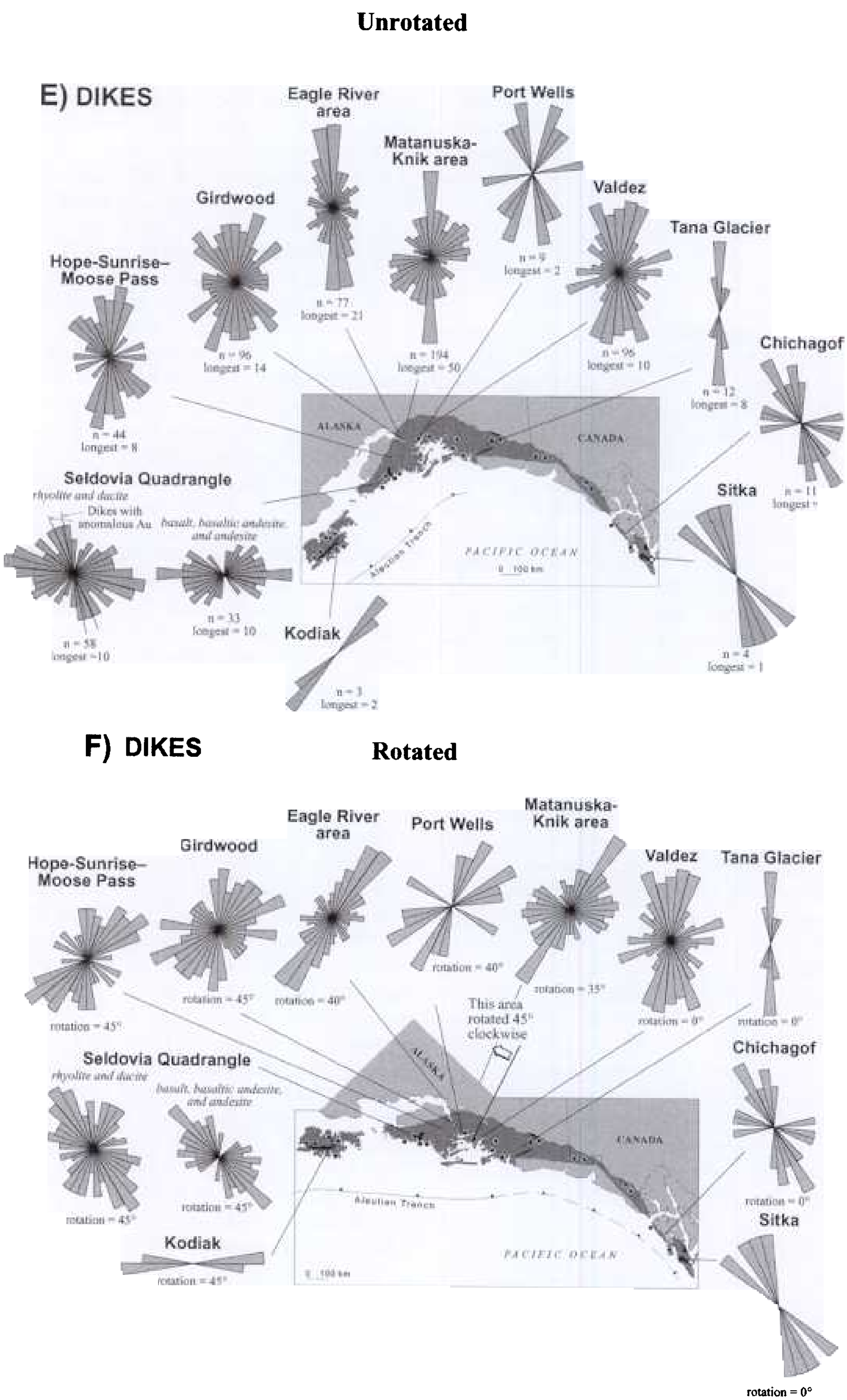


Figure 3 (*continued*).

information. A more complete description of the structural characteristics, data sources, geologic setting and crosscutting relationships, and age constraints can be found in the GSA Data Repository[1]. The repository differs significantly from the compilation of Haeussler and Bradley (1993) in that it summarizes information from each of the regions in more detail and from a number of areas not discussed below. It also includes data from the Sitka and Chichagof districts, which were not in the compilation of Haeussler and Bradley (1993).

Sitka District

This area encompasses lode-gold mines and prospects near Sitka of Baranof Island in southeastern Alaska (Fig. 1). It is underlain by the prehnite-pumpellyite facies Sitka Graywacke and Kelp Bay Group. Bedding and cleavage in the Sitka Graywacke, and compositional layering in the Kelp Bay Group, strike northwest and dip steeply (Fig. 3A). Four Sanak-Baranof belt plutons lie within 15 km of the Sitka district on Baranof Island, including the large (~760 km^2) Crawfish Inlet pluton. Dikes cut both the Sitka Graywacke and the Kelp Bay Group; these are not dated but are compositionally the same as isotopically dated plutons. On a broad scale, the Paleogene dikes (felsite and diorite) appear to strike parallel to the structural grain (Fig. 3E); in detail, however, dikes are at a 15°–30° clockwise angle to the strike of bedding and cleavage.

A $^{40}Ar/^{39}Ar$ age of 49.4 ± 0.4 Ma on sericite from vein quartz at the Lucky Chance Mine (Haeussler et al., 1995) is similar to a U/Pb zircon date of 50 Ma on the Crawfish Inlet pluton. Therefore, this mine and presumably seven other mines and prospects are part of the Sanak-Baranof belt. The veins, which typically occupy faults, have remarkably consistent attitudes: They strike northwest or west-northwest, and dip steeply to the north (Fig. 3B). The most compelling evidence of the fault kinematics is from the Golden Eagle (or Liberty) mine, where a gold-mineralized northwest-striking fault displays dextral slickenside steps. Numerous other gold-quartz veins in the area have the same general attitude and are likely along dextral faults but have not yielded kinematic data. In summary, the mineralized faults suggest a north-trending maximum shortening axis. The relative age of dikes and gold mineralization on Baranof cannot be proven, because isotopic ages of the two overlap (Haeussler et al., 1995). However, faults similar in structural style and orientation to mineralized faults do locally cut some Tertiary dikes, which suggests the gold-quartz mineralized faults are younger than the intrusions—consistent, as will be shown, with crosscutting relationships in other districts.

[1]GSA Data Repository item 2003124, Summary of structural data from gold mines, prospects, and mineral occurrences in the accretionary complex of southern and southeastern Alaska, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, at www.geosociety.org/pubs/ft2003.htm, or on the CD-ROM accompanying this volume.

Chichagof District

Western Chichagof Island is underlain by the prehnite-pumpellyite facies Sitka Graywacke and Kelp Bay Group. Bedding and cleavage in the Sitka Graywacke, and compositional layering in the Kelp Bay Group, strike northwest and dip steeply (Johnson and Karl, 1985; Fig. 3A). Plutons lie 10 km to the south and southwest of the locus of mining activity, as well as 15–20 km to the northwest (Loney et al., 1975). $^{40}Ar/^{39}Ar$ ages on biotite from these intrusions range between 50.3 and 51.4 ± 0.1 Ma (Taylor et al., 1994; see also Fig. 2). A few aplite dikes cut the Sitka Graywacke in mines and prospects in the Chichagof District. They appear to be compositionally similar to the Sanak-Baranof intrusions and different from basaltic dikes of late Tertiary age (Johnson and Karl, 1985). Similar to the Sitka District, the dikes mostly strike north-northwest, nearly parallel, but commonly at a 15°–30° clockwise angle, to the structural grain (Fig. 3E).

The Chichagof district had by far the largest gold production of all the ridge subduction-related gold deposits, with more than 24,900 kg (800,000 oz) produced primarily from the Chichagof and Hirst-Chichagof mines. A total of 60 mines and prospects are within this district. There are no isotopic ages on any of the gold-quartz veins cutting the sedimentary rocks. Taylor et al. (1994) obtained $^{40}Ar/^{39}Ar$ ages on muscovite and fuchsite of 51.9 and 52.1 ± 1.1 Ma from the Apex and El Nido mines, which are part of the same gold district but lie 5 km east of the Chugach accretionary complex. (The gold-bearing quartz veins in these mines have a similar structural style to those at the larger Chichagof and Hirst-Chichagof mines.)

All but a few of the gold-bearing quartz veins in this district are within faults that strike northwest and dip steeply southwest (Fig. 4; Reed and Coats, 1941), and many of these lie near the Border Ranges fault (Roeske et al., 1992; Smart et al., 1996). Further evidence for focused fluid flow associated with the Border Ranges fault are the Golden Hand and New Chichagof Syndicate groups of mines that lie virtually on top of the Border Ranges fault, and the other mines define a trend parallel to the fault. At the Chichagof and Hirst-Chichagof mines, both of which are on northwest-striking faults, slickenlines consistently plunging 30° NNW indicate reverse-dextral motion (Figs. 3C, 4). In all but one instance, faults with gold-quartz veins cut Sanak-Baranof belt intrusions. The one exception is on the Hirst-Chichagof fault, where an aplite dike intruded between layers of banded quartz (see Reed and Coats, 1941, plate 23) and was later cut by the fault and gold-quartz veins. This is the only gold occurrence where a dike intruded along a fault, and the relationship indicates that faulting, gold-mineralization, and magmatism were broadly coeval. Fault zones containing thick gouge zones with no quartz veins cut all gold-quartz mineralized features and are subparallel to the main mineralized faults.

Tana Glacier Area

In this region, the earliest deformation is a regional WNW-striking layer-parallel slaty and phyllitic cleavage that

Figure 4. Photograph looking northwest along the Chichagof fault at the Chichagof Mine in southeastern Alaska. The gold-quartz mineralized fault dips steeply to the southwest. Near the scale bar (long bar is 10 cm), slickenlines plunging 30° to the southwest show mineralization was along a reverse-dextral fault. The main gold-quartz vein is visible in the top center of the photograph and is highly ribboned. Gold and sulfides are also found in veins throughout the fault zone. Rock fragments within the fault zone to the right (northeast) of the main vein and above the scale bar are cut by quartz veins, and these are offset on later faults. To the left of the main vein is a gouge zone, with no quartz veining. Similar gouge zones offset all gold-bearing quartz veins, both within the Chichagof Mine and at all mines in the southern Alaska accretionary complex.

developed during accretion and subsequent shortening (D_1 of Pavlis and Sisson, 1995). High-T (~650 °C), low-P (~300 MPa) amphibolite-facies metamorphism of the Chugach metamorphic complex followed (Sisson et al., 1989), and it was accompanied first by orogen-parallel extension with vertical contraction (D_2 of Pavlis and Sisson, 1995) and then by subhorizontal contraction perpendicular to the margin (D_3). D_2 and D_3 were ductile events, and both were accompanied by injection of melts. Large plutons are elongate parallel to regional structural trends (Winkler and Plafker, 1993; Pavlis and Sisson, 1995). Notable among these is the Mt. Tom White pluton, which outcrops over an 80 km length but is rarely wider than 5 km (Hudson and Plafker, 1982). Within the Chugach metamorphic complex, the second-youngest structures are a set of tonalitic dikes, which are inferred to be the same age as the large intrusions (Ti_3 of Pavlis and Sisson, 1995; Fig. 3E). Isolated dikes restore to a north-striking orientation, but larger bodies strike east-west and dip steeply to the north, parallel to regional structural trends. These are the only dikes in the Chugach metamorphic complex that can be confidently related to other structures in the present compilation. Pavlis and Sisson (1995) concluded they were intruded during dextral transpression. The youngest dikes in the Chugach metamorphic complex (Ti_4 of Pavlis and Sisson, 1995) are undated. These dikes locally have chilled margins, which were interpreted as indicating significant cooling of the metamorphic complex prior to their cooling. These dikes also have north-south strikes (Fig. 3E).

Gold mineralization is unknown in the amphibolite-facies rocks in this area, and moreover, none would be expected because the fluids involved in gold mineralization are thought to have originated from greenschist-to-amphibolite facies dehydration reactions (Goldfarb et al., 1986). Brabb and Miller (1962) reported lode gold in the lower-grade greenschist facies rocks in this region. Thus, the rocks in the Chugach metamorphic complex may be typical of the deeper-seated source region for the fluids involved in overlying gold mineralization.

Port Valdez District

This area includes road-accessible areas northeast of the town of Valdez and the Port Valdez gold district. Bedding and cleavage in the Valdez Group, and compositional layering in the McHugh Complex, strike west-southwest and dip steeply (Fig. 3A). Although most mines and prospects lie within the Valdez Group, a few small prospects in the southwestern part of this area lie in the Orca Group, both of which consist of turbidites at middle greenschist facies (Goldfarb et al., 1986). Orogen-parallel stretching lineations have also been measured in these rocks and are inferred to postdate development of phyllitic cleavage (Marty, 1994; Pavlis et al., this volume, Chapter 7). Marty (1994) and Pavlis et al. (this volume, Chapter 7) correlated these with orogen-parallel strains in the Tana Glacier area, which occurred at the time of peak metamorphism and thus at the time of ridge subduction. There are no large intrusions in the area, but there are at least a dozen andesite and dacite dikes that have been correlated with Sanak-Baranof belt intrusions (Plafker et al., 1992). The dikes most commonly strike north-south (Fig. 3E), which is roughly perpendicular to the strike of bedding and cleavage.

Structural data are available from 57 gold mines and prospects in the Port Valdez area. Gold-quartz veins generally strike northwest and dip steeply between 50° and 90° (Fig. 3B). At least 24 of the 57 gold occurrences with some structural data are apparently hosted by faults; shear sense is known for a few faults. Two dextral faults dip steeply and strike northwest, like the gold-quartz veins. Pickthorn (1982, p. 24 and 27) implied that these northwest-striking dextral faults are common and stated they are cut by east-striking sinistral faults. If these fault sets are considered together, the sense of offset is opposite what would be expected with a conjugate set. This suggests the fault sets are not related to the same stress regime. Only two of the 57 gold-quartz mineral occurrences are reported to be near dikes, and in both cases the veins cut the dikes; thus, gold mineralization is younger.

Port Wells District

This large area includes lode-gold occurrences around Port Wells and adjacent areas of western Prince William Sound.

Bedding in the middle-greenschist facies turbidites of the Valdez and Orca Groups generally strikes northeast (Fig. 3A). This area includes two age groups of plutons. The older set (ca. 54 Ma), represented by granitic plugs at the Granite and Homestake mines, belongs to the Sanak-Baranof intrusive suite (Haeussler et al., 1995); the younger set is 34–36 Ma (Tysdal and Case, 1979; Nelson et al., 1985; Bradley et al., 1993; Nelson et al., 1999). Dikes, which are undated and could belong to either set, generally strike north-northeast and dip steeply at a high angle to bedding.

The orientation and sense-of-offset of gold-quartz mineralized faults is variable. Most subeconomic quartz veins in the district strike northwest and dip steeply (Fig. 3B). Many of the mined gold veins, however, strike northeast. About half of the gold-quartz veins are demonstrably within a fault. We measured three dextral faults with northwest strikes, and Hoekzema et al. (1987) reported a northeast-striking dextral fault. We found one north-northwest–striking gold-quartz mineralized sinistral fault. We measured five north-south–striking normal faults with steep easterly dips, three of which were gold mineralized.

Gold-quartz veins lie within a few hundred meters of intrusions at 17 of 49 localities. At 11 occurrences the veins cut intrusions, and thus the gold mineralization postdates magmatism. It is remarkable there are this many gold-quartz veins that cut dikes, because of the abundance of ca. 35 Ma intrusions in the area, which postdate the Sanak-Baranof belt. Therefore, these dikes must be related to the Sanak-Baranof belt.

Stüwe (1986) reported three types, or generations, of quartz veins in the Port Wells district. Type 1, the oldest, are boudinage-related veinlets cutting competent beds and veinlets paralleling the structural fabric. Goldfarb et al. (1986) referred to these early, bedding-parallel veins as metamorphic quartz segregation features, and we find they are common throughout the Kenai and Chugach Mountains. Fisher and Byrne (1990) documented similar veins on Kodiak Island (their D_2 veins). Stüwe's (1986) Type 2 veins are the gold-quartz veins, and are younger than the intrusions. Stüwe's (1986) Type 3 veins occur as networks, stockworks, and healed fracture fillings with no consistent orientations. The only reported crosscutting relationship among the gold-quartz veins is in Harriman Fiord, where Stüwe (1984) found an older sulfide-mineralized vein (N41°E/65°N) cut by a younger, barren, drusy white vein (N64°E/86°N). The fact that both veins are similar in orientation to veins elsewhere, such as in the Hope-Sunrise–Moose Pass area (see below), and that the younger veins are clockwise of the older veins, suggests similar structural histories for both areas.

Chugach Mountains near Anchorage (Matanuska-Knik and Eagle River Areas)

Bedding and cleavage in the Valdez Group, and compositional layering in the McHugh Complex, strike east-west in the drainages of the Matanuska and Knik Glaciers (Winkler, 1992). There are no large intrusions, but dacitic dikes that cut across the regional lower greenschist facies fabric in the Valdez Group and McHugh Complex (Burns et al., 1991; Winkler, 1992) are common. Locally, these intrusions are sills (Little and Naeser, 1989). Winkler's (1992) map of the area shows a similar dike swarm in the Eagle River drainage (Fig. 3E), which also cuts across the regional structural fabric in the McHugh Complex and Valdez Group rocks. Both dike swarms show a strong north-south preferred orientation (Fig. 3E). Two gold occurrences are present within this region (Capps, 1916), and their post-cleavage, high-angle, brittle faulting structural style is similar to the veins found elsewhere.

Girdwood District

The Girdwood district lies within laumontite to lower greenschist facies (Goldfarb et al., 1986) Valdez Group rocks and has a structural style typical of the Valdez Group, but it has anomalous orientations. Bedding and cleavage strike east-northeast and dip steeply (Fig. 3A), in contrast to the more typical north-northeasterly strikes in this region. Lode-gold mines and prospects in the Girdwood district are concentrated near small granitic intrusions, including the Crow Pass pluton, which has the map pattern of a tadpole-like dike. Most dikes have north-northeasterly strikes (Park, 1933). Seven of nine gold occurrences are usually within a few tens of meters of one or more dikes. Two of the nine documented gold occurrences crosscut a dike or associated hornfels; therefore, gold mineralization is younger than near-trench magmatism. Most of the gold-quartz veins, including the most productive ones (Hoekzema et al., 1987), strike roughly east-west; some of these veins are dextral faults. A few gold-quartz veins with unknown offset strike approximately north-south. Two nonmineralized, probably younger, gouge-filled dextral faults strike northwest-southeast.

Upper Kenai Peninsula (Hope-Sunrise and Moose Pass Districts)

These areas lie entirely within lower greenschist facies Valdez Group rocks (Mitchell, 1979). Bedding and cleavage strike north-northeast and dip steeply. Large plutons are absent, but felsic dikes are abundant. Mitchell (1979, p. 35) found that most dikes have northwest strikes, but the two longest and economically most significant dikes trend north-northeast (015°) (Hoekzema et al., 1987, p. 38). These are the Gilpatrick and Palmer Creek dikes, which are mapped as 18 and 12 km long, right-stepping intrusions.

Gold-bearing quartz veins have a wide range of orientations, and most are steeply dipping, although veins with a north-south strike are slightly more common. Twenty-two of 63 gold occurrences in our database are clearly along faults, and most are along north-northeast–striking dextral faults that are subparallel to, and at seven localities, cut the 015°-striking dikes. The mineralized faults are cut by a later set of dextral faults that strike northeast to east-northeast. No sinistral- or reverse-motion mineralized faults were recognized in this area, but there are two east-west–striking normal faults.

The approximate parallelism between gold-quartz mineralized dextral faults and bedding in the Hope-Sunrise–Moose Pass area is similar to the Girdwood area. In the Girdwood area, however, most dikes are perpendicular to bedding, whereas in the Hope-Sunrise–Moose Pass area, the dikes are subparallel to bedding. Another similarity of the two areas is the presence of barren faults oriented about 30° clockwise of the gold-bearing faults. Curiously, the orientations of bedding, mineralized dextral faults, and barren dextral faults in the Girdwood area are all oriented approximately 70° clockwise of the same structures in the Hope-Sunrise–Moose Pass areas and 70° clockwise with respect to regional orientations of bedding (Winkler, 1992). We therefore suggest a clockwise vertical-axis rotation of the Girdwood area after gold-quartz mineralization and after movement on the barren faults. Although dikes are not obviously rotated, they have a much wider range of orientations in the Girdwood area than in the Hope-Sunrise–Moose Pass area.

Lower Kenai Peninsula (Nuka Bay District and Seldovia Quadrangle)

The lower Kenai Peninsula is underlain by the lower greenschist facies Valdez Group and the McHugh Complex. The regional orientation of bedding and cleavage is north-northeast–striking and moderately to steeply dipping to the northwest (Bradley et al., 1999).

The oldest structures that postdate accretion record orogen-parallel extension. In the Nuka Bay mining district (Richter, 1970; Fig. 1), barren, northwest-southeast–striking quartz veins strike perpendicular to thick sandstone beds (Fig. 5A). These veins are unrelated to faults and are steeply dipping with subhorizontal quartz mineral fibers. At one locality, stretched pebbles are parallel to the quartz fibers. At another, a quartz vein perpendicular to bedding was hornfelsed in the margins of Sanak-Baranof belt intrusions. The quartz vein in outcrop has relict fibrous forms (Fig. 5B). A thin section shows evidence of hornfels with abundant small equant quartz grains in a crystalloblastic fabric, and a few relict larger elongate quartz grains (Fig. 5C). Both the geometry and microscopy of the quartz vein indicate that margin-parallel extension occurred prior to intrusion of the pluton.

The Seldovia quadrangle includes three large biotite-granodiorite plutons: the Nuka, Harris Bay, and Tustumena, which are likely connected at depth because of their proximity and similar orientation (see also Kusky et al., this volume, Chapter 12). The three largest plutons are elongate along a north-south trend, and swarms of mafic, intermediate, and felsic dikes are common. The mafic and felsic dikes have westerly strikes, with a subordinate northwest-striking group of felsic dikes (Fig. 3E). Geochronology indicates dikes have the same ages as plutons (Bradley et al., this volume, Chapter 1). At one locality north of Harris Lagoon, however, sills (dipping ~35° to the WNW) subparallel to the larger intrusions are cut by steeply dipping dikes

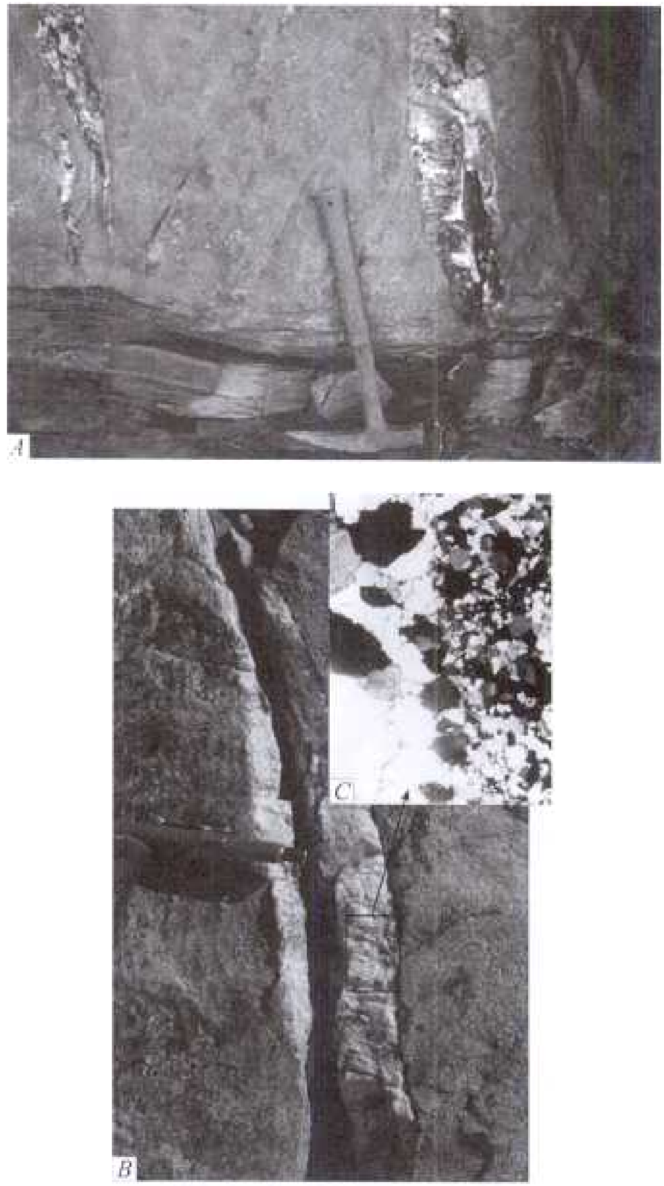


Figure 5. A: These veins with subhorizontal quartz fibers in the Nuka Bay area are oriented perpendicular to bedding and indicate orogen-parallel extension. The veins cut the graywacke but not the slate. B: Hornfelsed vein with subhorizontal quartz fibers parallel to the pencil from the margin of a pluton in the McCarty Fiord area. This relationship demonstrates that orogen-parallel extension predated near-trench magmatism. C: Photomicrograph of quartz vein in Fig. 5B. Note the abundant small equant quartz grains that comprise the crystalloblastic fabric. The few larger and elongate quartz grains are probably relict fibrous quartz crystals.

(Fig. 6). This suggests a change in the strain regime between intrusion of the sills and plutons and the dikes.

The greatest concentration of gold occurrences is in the Nuka Bay area. Most gold-bearing quartz veins are within steeply dipping sinistral- faults that strike west—approximately perpendicular

Figure 6. Photograph is of a ~200 m high cliff face just north of Harris Lagoon in the eastern part of the Seldovia quadrangle (Fig. 1). The low-angle sills were intruded into Valdez Group graywacke before the steeply dipping dikes. This suggests there was a significant change in stress directions during intrusion of the sills versus intrusion of the dikes. We consider the dikes as related to extension during the later stages of ridge subduction.

to regional structural trends (Fig. 7). Some gold-quartz veins occur along dextral-lateral faults that strike northeast. The dextral and sinistral faults form a conjugate set and appear to be the same age. The acute bisector of the conjugate fault sets strikes northeast and indicates contraction subparallel to the regional strike of bedding. Most of the fractured dikes along which there was gold also strike northeast. This relationship suggests these dikes were intruded into the same stress regime that produced the strike-slip faults. Five of 15 mineral occurrences in the Nuka Bay area lie within, or at the margins of, dikes. There are also mineralized normal faults but no mineralized thrust faults. Mineralization in Thunder Bay, 25 km northeast of Nuka Bay, was on dextral-normal or normal-dextral faults. Most mineral occurrences in the Nuka Bay area were on faults with the same orientation but opposite sense of offset. The differences in fault offset between these two areas demonstrate significant differences in fault kinematics between areas not very far apart.

Sinistral, dextral, normal faults, and one thrust fault were observed to cut gold-bearing quartz veins. At least some brittle faulting postdated mineralization at all locations. Some of the late faulting is manifested by clay-rich gouge zones at the margins of the gold-bearing quartz veins/faults (Fig. 7). These gouge zones are typically less than 30 cm wide and consist of brecciated and altered wall rock fragments. Some gouge zones also contain a few thin quartz veins. It is uncertain whether these gouge zones represent movement on the faults soon after cessation of hydrothermal activity or whether they are substantially younger faults that reactivated older structures.

The youngest phase of brittle faulting occurred on faults filled with clay-rich gouge zones up to 10 m wide and with no quartz veins. These faults form prominent topographic lineaments that cut across all structures. In our examination of several of these faults in shoreline exposures, there was no indication of significant offset. In summary, there was orogen-parallel extension before Sanak-Baranof magmatism and orogen-parallel contraction during gold mineralization and dike intrusion.

Kodiak District

The prospects on Kodiak and adjacent islands are either in the Kodiak Formation or in diorite or granodiorite intrusions that cut the Kodiak Formation, with the exception of one prospect that cuts the Uyak Complex. All of the intrusions appear related to the northeast-striking Kodiak batholith because of similarities in composition, geometry, and age. Four of twelve prospects were described as being near numerous and persistent dikes, three are in structures that cut an intrusion, and one is at the contact of an intrusion. Extensive work has been conducted on early quartz veins associated with underthrusting of sediments beneath the accretionary prism (Fisher and Byrne, 1987, 1990; Vrolijk, 1987; Meyers and Vrolijk, 1986; Fisher and Brantley, 1992). These veins formed during or before zeolite to prehnite-pumpellyite facies (Sample and Moore, 1987) cleavage formation (Fisher and Byrne, 1990) and are thus easily distinguished from the gold-bearing quartz veins and faults that crosscut the cleavage.

Bedding and cleavage strike northeast (Moore, 1969). Dikes strike northeast, dip steeply, and are subparallel to the massive and elongate Kodiak batholith (Fig. 1). There are two main orientations of gold-quartz veins: northeast-striking and northwest-striking. The northwest-striking veins are approximately perpendicular to cleavage, and two of the gold-quartz veins are demonstrably in a fault zone. Two faults with an

Figure 7. This east-west–striking vein in the Nuka Bay area (locality 12 of Richter, 1970) is typical of many gold-bearing quartz veins. It dips steeply, is 30 cm wide, was deposited in a strike-slip fault (in this case sinistral), and has a 10 cm wide clay-rich gouge zone at the right (northern) margin. The wall rocks on the right side of the fault are graywackes, and the wall rock on the left margin is an aphanitic intermediate dike.

unknown sense of offset are at a 60° angle to bedding and are steeply dipping, and thus the late-fault orientations are not controlled by a pre-existing fabric.

DISCUSSION

Structural History of the Accretionary Complex

The Sanak-Baranof belt of intrusions along Alaska's Pacific margin provide us with the special opportunity to discriminate between pre-, syn-, and post-ridge subduction structures (Fig. 8). By examination of crosscutting relationships, we find a common sequence of events along the length of the accretionary complex.

1. Underplating, offscraping, regional metamorphism, and contractional deformation. Offscraping and underplating of sediments on the subducting plate was the fundamental step in the construction of the accretionary complex. Numerous studies have focused on this aspect of the development of the southern Alaska accretionary complex (Sample and Moore, 1987; Byrne, 1984, 1986; Moore and Allwardt, 1980; Bradley and Kusky, 1992; Kusky et al., 1993; Kveton, 1989; Clendenen, 1991). On Kodiak Island, Fisher and Byrne (1990) found there were two major episodes of fracturing and quartz mineralization related to underthrusting and underplating. Subsequently, the Valdez Group turbidites and its correlatives were then metamorphosed up to middle greenschist facies (M. Miller, 1993, personal commun.; Goldfarb et al., 1986; Sample and Moore, 1987). This low-grade metamorphism and deformation is exhibited in a common slaty and phyllitic cleavage and associated metamorphic segregation quartz veins (Goldfarb et al., 1986; Stüwe, 1986). All of these events predated passage of a trench-ridge-trench triple junction. If this triple junction is related to the Kula–Farallon–North America triple junction, then the Valdez Group and its correlatives were offscraped or underplated from the Farallon plate (Bradley et al., 1993), not from the Kula plate (Plafker et al., 1994; Wallace and Engebretson, 1984), because the Kula–Farallon–North America triple junction was farther north than previously assumed.

2. Orogen-parallel extension. We find evidence of orogen-parallel extension in the Nuka Bay and Sitka areas, and other workers find evidence for it in the Valdez and Tana Glacier areas (Marty, 1994; Davis et al., 1998; Pavlis et al., this volume, Chapter 7). Orogen-parallel extension may have occurred either prior to ridge subduction, as in the Nuka Bay area, or it may have occurred at the onset of ridge subduction, as in the Tana Glacier area. Orogen-parallel extension is a common occurrence in modern and ancient forearc settings (e.g., Avé Lallemant and Guth, 1990; McCaffrey, 1996), and it need not be related to ridge subduction processes.

3. Near-trench magmatism and high-T, low-P metamorphism. The locus of near-trench magmatism migrated along the Gulf of Alaska margin, from ca. 61 Ma near Sanak Island to ca. 50 Ma on Baranof Island (Bradley et al., 1993 and this volume, Chapter 1). Near-trench magmatism postdated margin-parallel extension in the Nuka Bay and Sitka areas and was synchronous with margin-parallel dextral shear in the Tana Glacier area. Plutons were emplaced in some areas, but steeply dipping dikes are most common. Sills are uncommon.

4. Gold mineralization in strike-slip or extensional setting. In all cases but one, gold-quartz veins cut intrusions. The one exception is at the Hirst-Chichagof mine in southeastern Alaska where some veining and faulting occurred prior to intrusion of a dike along a fault. This exception indicates that faulting, veining, and near-trench magmatism were broadly coeval. Moreover, the $^{40}Ar/^{39}Ar$ ages of gold-bearing quartz veins and nearby near-trench intrusions are indistinguishable and therefore link mineralization to magmatism (Haeussler et al., 1995). There was widespread brittle deformation of the accretionary complex when there was a slab window beneath the forearc. All of the faults hosting the gold-quartz veins are either strike-slip or extensional (we discuss this more completely in a following section). Contractional deformation played no role in the emplacement of these veins. Upper greenschist to amphibolite facies dehydration reactions appear necessary to produce the appropriate vein-forming fluids (Goldfarb et al., 1986). In all cases, we consider it likely that the sources of the vein forming fluids are rocks below the present level of exposure. Rocks like the high-*T*, low-*P* Chugach metamorphic complex (Sisson et al., 1989) were probably in the source region for the vein-forming fluids.

5. Right-lateral brittle faulting without fluid flow on margin-parallel faults. Unmineralized right-lateral brittle faults with gouge zones were active subsequent to veining and crosscut mineralized faults. In southeastern Alaska, these late faults are subparallel to the earlier mineralized structures. In south-

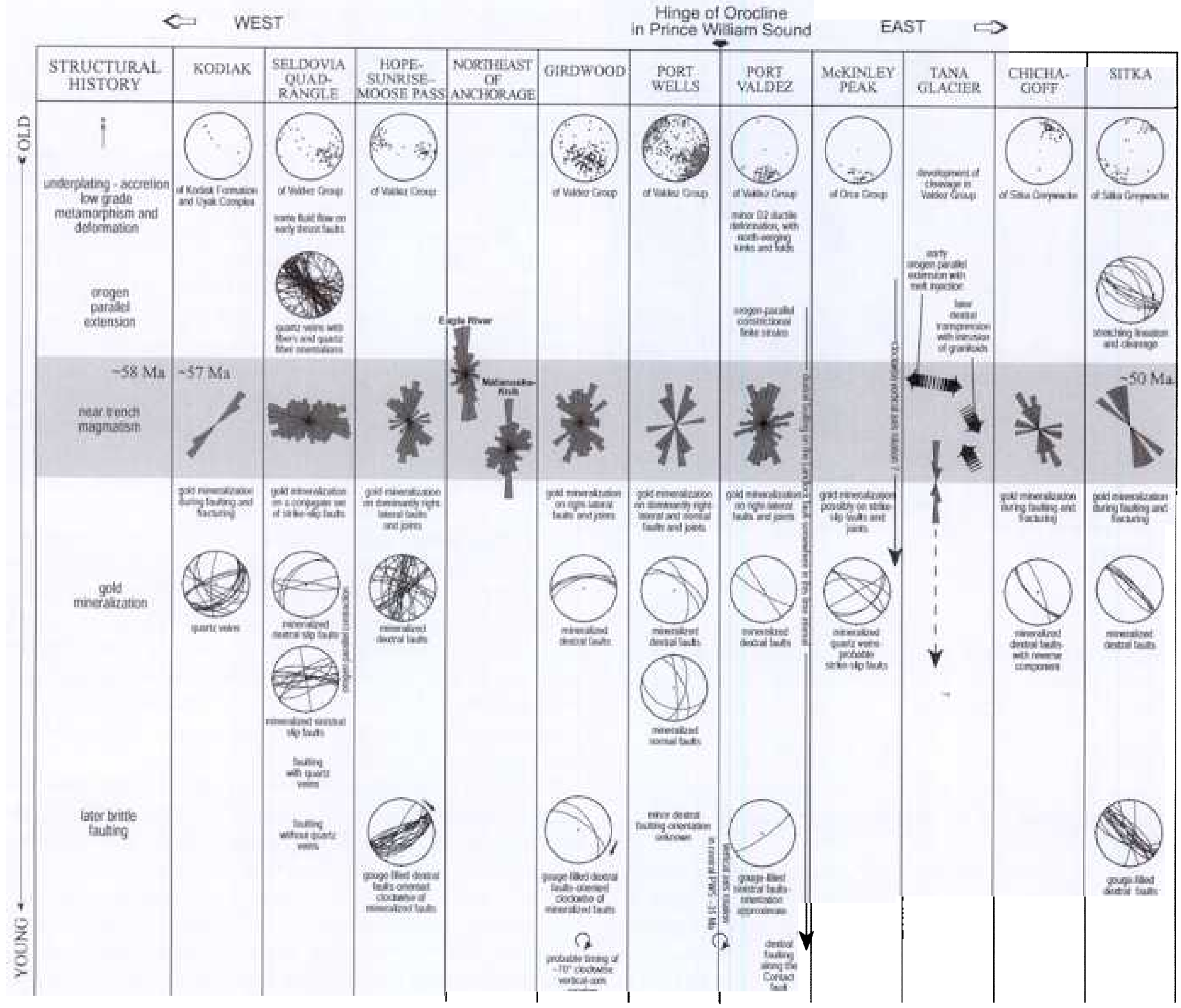


Figure 8. Graphical structural history of the southern and southeastern Alaska accretionary complex. Stereonets and rose diagrams (from Fig. 3) show orientations of structures. Note near-trench magmatism is time transgressive from ca. 57 to 58 Ma near Kodiak Island to ca. 50 Ma on Baranof Island. Gold mineralization is also time transgressive (Haeussler et al., 1995), and other events may be time transgressive. Events younger than ca. 30 Ma are not shown. Blank boxes do not imply an event did not occur, but rather an event has not been observed in a particular area.

central Alaska, these dextral faults are parallel to the Aleutian trench, strike northeast-southwest, and are typically oriented 15°–30° clockwise of the largest mineralized structures.

It is puzzling why these faults in south-central Alaska are oriented clockwise of the older mineralized faults. Continued dextral shear along the margin and vertical-axis block rotations do not explain the relationships between the fault sets. The faults might be synthetic Riedel shears that emanated from vein-parallel dextral faults. This explanation is consistent with the present data, and it may provide the simplest interpretation.

6. Vertical axis rotations. Sometime between deposition of the gold-quartz veins and ca. 30 Ma, vertical axis rotations occurred in central Prince William Sound near the hinge of the orocline (Haeussler and Nelson, 1993; Nelson et al., 1999). These rotations were probably caused by oroclinal bending in the area and are not documented elsewhere. As previously indicated, ~70° clockwise vertical-axis rotation may have occurred in the Girdwood area. Another area within the accretionary complex where vertical axis rotations have been proposed is in eastern Prince William Sound. Bol and Roeske (1993) argued for clockwise rotations during accretion of Orca Group sedimentary rocks and during tightening of the hinge of the orocline. Finally, Stamatakos et al. (1988) found paleomagnetic evidence for clockwise block rotations of about 50° along the Border Ranges fault in the Matanuska Valley. Rotations may also have affected rocks in the adjacent accretionary complex to the south.

Interpretation of Fault Kinematics and Structures Hosting Gold-Quartz Veins

We conclude there was widespread deformation of the forearc above the slab window at the time of ridge subduction because the gold-quartz veins are linked to ridge subduction by geochronology (Haeussler et al., 1995) and because the veins typically lie in faults distributed over broad regions of the accretionary complex.

All gold-quartz mineralized faults are strike-slip or normal motion. We found no mineralized thrust faults. There is a remarkable consistency of right-lateral strike-slip faults in southeastern Alaska and no dominant orientation of gold-quartz mineralized faults in south-central Alaska. Nonetheless, right-lateral faults at a low, but variable, angle to the regional strike of bedding and cleavage are perhaps most common in south-central Alaska. Despite the general consistency in sense of offset in some areas, considerable variation exists in the kinematics of mineralized faults over distances of a few tens to a hundred kilometers. In Nuka Bay, for example, east-west–striking sinistral faults are most common, in contrast to at Thunder Bay, 25 km to the northeast, where east-west–striking normal-dextral faults are most common. A different orientation and sense of offset is most common in the upper Kenai Peninsula area, 125 km to the northeast, where north-northeast–striking dextral faults are most common. However, these faults could be considered as conjugate to the east-west–striking sinistral faults in Nuka Bay. In Nuka Bay, the kinematics of the gold-quartz mineralized conjugate fault set imply margin-parallel contraction during gold mineralization. There are not enough measured normal-fault orientations with which to draw firm conclusions (Fig. 3D), but most are oriented at a high angle to the regional strike of bedding and cleavage, perhaps allowing strike- or margin-parallel extension.

Bradley and Kusky (1990) and Kusky et al. (1997) described three sets of quartz-mineralized brittle faults along Turnagain Arm, southeast of Anchorage, which together accommodated northwest-southeast–directed contraction. These faults are probably age-equivalent to the gold-quartz mineralized faults because of relative timing relationships and because their structural style is comparable. The kinematics of these fault sets differ from the adjacent upper Kenai Peninsula areas, because along Turnagain Arm the dextral faults are E-W, whereas in the upper Kenai Peninsula areas the dextral faults strike NNE. Thus, although local structural and kinematic patterns can be found, the pattern of orthorhombic faulting in Turnagain Arm cannot be readily extended to other areas. Perhaps the principle of orthorhombic faulting may apply to other areas if enough faults are measured.

The gold-quartz mineralized faults in southeastern Alaska lie along late faults near a major crustal-scale strike-slip fault system—the Border Ranges fault (e.g., Smart et al., 1996), whereas those in south-central Alaska do not. Presumably, ore-forming fluids were channeled more effectively near this large structure, which led to larger deposits than in south-central Alaska. The Chichagof district in southeastern Alaska produced more than 800,000 oz of gold, in contrast to smaller but more widespread veining in south-central Alaska, where none of the mines produced more than 50,000 oz of gold. Gold mineralization is not associated with the Border Ranges fault in south-central Alaska (Fig. 1). This might be due to a smaller component of margin-parallel shear in south-central Alaska during the time of ridge subduction, which resulted in the diffuse network of strike-slip and normal faults.

It is likely most of the gold-quartz veins were deposited within active faults because many faults have crosscutting relationships showing evidence of movement during veining. Thus, the movement on the faults allowed multiple pulses of fluid to migrate upward and be deposited in the faults and nearby joints. Joints are probably subsidiary to the faults because, for example at the Chichagof Mine, there are ribbon quartz veins within the main fault zone and within joints oriented subperpendicular to the main fault zone. Thus, it appears ore-forming fluids entered the joint systems in multiple pulses, in the same way as in the main fault zone. After gold-quartz deposition, faulting without fluid flow formed gouge zones along the margins of most vein systems. These faults are ubiquitously margin-parallel gouge-filled dextral faults, which suggests (1) there was a significant component of simple shear on this margin, and (2) the faults formed at a time the trailing oceanic plate had a significant (≥30°) obliquity of subduction (Jarrard, 1986).

During west-to-east passage of the slab window during ridge subduction, we consider the stress and strain regime in the accretionary complex to be related to at least several factors: (1) the relative motions of the forward and trailing oceanic plates, (2) the slab window (perhaps an absence of relative motion with upwelling asthenospheric mantle beneath the forearc), and (3) the geometry of the plate margin. The fact that the gold-quartz veins cut near-trench intrusions formed during passage of the slab window indicates the gold-quartz veins and their host faults and joints formed either above the slab window or above the trailing plate. The relative motion of the trailing oceanic plate would probably affect some region above the slab window as well.

It is not possible to provide a single kinematic framework for all the gold-quartz mineralized faults, but this may be due, in part, to the geometry of the early Tertiary plate margin and the relative motions of the subducting plates. In southeastern Alaska, dextral strike-slip faults developed at a low angle to the regional structural fabric at the time of gold-quartz mineralization. Jarrard (1986) found that when convergent plate obliquities exceed 30°, trench-parallel strike-slip faults develop. The fact that all gold-quartz mineralization in southeastern Alaska was on dextral faults indicates a strong dextral component of the trailing plate relative motion. However, in south-central Alaska, the gold-quartz mineralized faults are not as tightly clustered in their orientations (see Figs. 3C, 3D). We interpret these characteristics as indicating (1) there was a higher degree of simple shear in southeastern Alaska versus southern Alaska, and (2) the obliquity between the trailing plate and the forearc was not as high as in southeastern Alaska. This may be explained by either a change in the relative motion of the trailing, possibly Kula, plate with respect to the forearc, or there was some pre-existing bend to the south-central Alaska margin, or both. There was a significant change in the Farallon–North America plate motion during anomaly 23R (Atwater and Severinghaus, 1989), which corresponds to ages of 51.75–52.35 Ma (Berggren et al., 1995). At this time, the relative motion of subduction became more dextrally oblique by about 15°–20° with respect to the Alaskan margin. Isotopic ages of near-trench intrusions and the gold-quartz veins indicate the subducted ridge lay between south-central and southeastern Alaska at that time (Bradley et al., 1993 and this volume, Chapter 1; Haeussler et al., 1995). Therefore, it is likely that at least some of the change in the structural style of the gold-quartz mineralized faults is due to this plate motion change. As discussed earlier, the timing of ridge subduction with respect to development of the orocline is uncertain based on paleomagnetic and geochronologic constraints, but structural considerations may favor development ca. 35 Ma (Haeussler and Nelson, 1993; Nelson et al., 1999). Nonetheless, the most recent model for development of the orocline suggests a pre-existing ~45° bend in the Alaskan margin that was tightened later in Tertiary time (Bol and Gibbons, 1992). Our data from the gold-quartz mineralized faults are also consistent with a pre-existing bend in the south-central Alaska margin. We consider the diffuse set of strike-slip and normal faults in south-central Alaska as more likely to have formed where trailing plate convergence vectors are not highly oblique (>30°), whereas in southeastern Alaska there apparently was a high degree of obliquity. Therefore, both the geometry of the ancient Alaskan margin as well as a change in relative plate motions may be responsible for the kinematics and orientation of gold-quartz mineralized faults in different areas.

Interpretation of Dike Orientations

Dikes can also provide information on the direction of extension above the slab window. If a dike is emplaced into a homogenous isotropic medium undergoing extension, the dike will be oriented normal to the least compressive stress direction (σ_3). For a dike to intrude along pre-existing planes of weakness in Earth's crust, magmatic pressure must exceed the normal component of the regional stresses on the fracture plane. We conclude that the regional strike of bedding and cleavage did not strongly influence the orientation of dikes for the following reasons. (1) Away from large plutons, dike swarms show broad regional trends (Fig. 3E). Dike orientations do not appear randomly oriented nor serially correlated with a particular regional strike of bedding or cleavage. (2) Although there are locations where intrusions are parallel to bedding and cleavage, such as in the northern Chugach Mountains (Little and Naeser, 1989), in detail dikes most commonly cut across the pre-existing fabric, commonly at a low angle. The strike of bedding and cleavage is usually consistent within a region and it is remarkable how few dikes are parallel to it. (3) Delaney et al. (1986) found that when dikes are emplaced along pre-existing joints in regions of active tectonism, joints suitably oriented for dike intrusion have a narrow range of orientations, and dikes are likely to be good indicators of principal stress directions at the time of emplacement even when the difference in magnitude between the principal and intermediate stress directions is not large. Finally, we reiterate that the one paleostress orientation that we can be confident of is σ_3, which must be roughly perpendicular to the dike orientation. σ_1 and σ_2 should lie within the plane of the dike, but the orientation of the axes is uncertain.

Although it is simplest to consider dike orientations in their present orientation, it is also useful to evaluate their orientation prior to oroclinal bending. We use the oroclinal bending model of Bol and Gibbons (1992), and we choose to "un"rotate the dike orientations in the Kodiak to Port Wells region 45° clockwise, the Matanuska-Knik area 35° clockwise—because it is closer to the hinge of the orocline—and consider the remaining regions in their in situ orientation (see Fig. 3F).

In southeastern Alaska, most dikes in both the Sitka and Chichagof districts strike northwest, indicating a southwest-northeast component of extension. Because a dike intruded a northwest-striking dextral fault in the Hirst-Chichagof mine, it appears that dextral shear, not pure shear, occurred at the time of dike emplacement. In south-central Alaska, the areas between Hope-Sunrise–Moose Pass and Matanuska-Knik all have northeasterly restored dike strikes, and the Valdez and Tana Glacier area have northerly dike strikes (Fig. 3F). If we consider these areas together, the dike strikes indicate northwest-southeast extension during emplacement of the dikes. The two regionally extensive right-stepping en echelon dikes in the upper Kenai Peninsula area are indicative of a component of margin-parallel dextral shear during intrusion of the dikes. Pavlis and Sisson (1995) concluded there was right-lateral shear soon after intrusion of the Ti_3 generation of dikes in the Tana Glacier area. Therefore, although the inferred timing of deformation in these two areas is slightly different, they both appear related to margin-parallel dextral shear. Nonetheless, in the lower Kenai Peninsula, the dikes are approximately perpendicular to the margin, and thus extension was subparallel to the margin. This extension direction is similar to that inferred prior to ridge subduction based on the subhorizontal quartz mineral fibers. This extension direction is perpendicular to the σ_3 orientation in the upper Kenai Peninsula to Tana Glacier region and could be due to either a flip in σ_1 or σ_2, in addition to the σ_3 orientation.

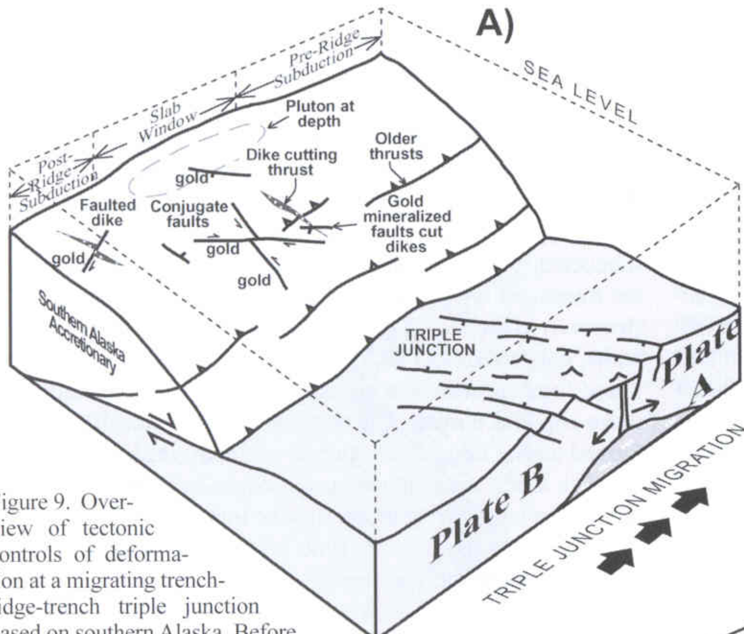
Overall, differences in dike strikes between different areas cannot be explained by a single kinematic regime, but indicate considerable variability in the strain pattern associated with the slab window and the trailing plate.

A Model for Complex Brittle Deformation at a Migrating Trench-Ridge-Trench Triple Junction

At any convergent margin with an accretionary complex where ridge subduction occurs at a migrating trench-ridge-trench (TRT) triple junction, we envision three configurations in which the forearc can respond (see Fig. 9). Before ridge subduction, Plate A (Fig. 9) influences the shape of the accretionary complex and the processes in the forearc by controlling the basal traction by its relative motion with respect to the forearc and by a characteristic basal friction. After ridge subduction, Plate B (Fig. 9) influences the shape of the accretionary complex for the same reasons. The forearc will have different relative motions to Plate B than Plate A, and this difference will be accommodated in the vicinity of the triple junction.

The effects of the passing slab window also need to be considered. At the base of the forearc, there is no longer an oceanic plate beneath the accretionary complex, and there will be less basal friction than during "normal" subduction. Moreover, because both the forward and trailing oceanic plates are moving apart relative to each other away to the sides of the slab window, the region above the slab window would inevitably experience extension (unless the velocity of the spreading center toward the trench is significantly greater than the spreading rate). In addition, the region above the slab window receives a large thermal pulse. Therefore, in the region above the slab window, the forearc crust will respond to extension caused by the relative motion of Plate A to B, the decreasing influence of the pull of Plate A, the increasing influence of the pull of Plate B, and the thermal pulse and decreased(?) basal friction from the slab window.

This model provides insights into the structural geology of the gold-quartz occurrences and the near-trench dikes in southern Alaska by predicting that the zone above the slab window will have a complex but dominantly extensional or strike-slip



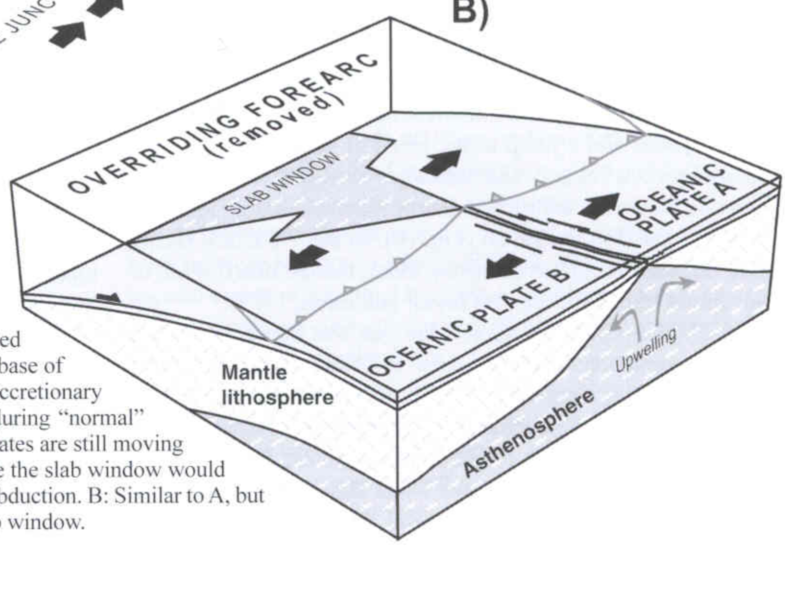


Figure 9. Overview of tectonic controls of deformation at a migrating trench-ridge-trench triple junction based on southern Alaska. Before ridge subduction, Plate A influences the shape of the accretionary complex and the processes in the forearc by controlling the basal drag by its relative motion with respect to the forearc and by a characteristic basal friction. After ridge subduction, Plate B influences the shape of the accretionary complex for the same reasons. The forearc will have different relative motions to Plate B than Plate A, and this difference will be accommodated in the vicinity of the triple junction and slab window. At the base of the forearc, there is no longer an oceanic plate beneath the accretionary complex, and there may be much less basal friction than during "normal" subduction. Because both the forward and trailing oceanic plates are still moving apart along the margins of the slab window, the region above the slab window would experience extension. A: Block diagram of region of ridge subduction. B: Similar to A, but with forearc removed, showing a possible geometry of a slab window.

structural history. First, we suggest that prior to passage of the triple junction, there was a significant margin-parallel component to the relative plate motions, as indicated by the margin-parallel extension in the Nuka Bay, Valdez, and Sitka areas. The margin-parallel extension in the Tana Glacier area at the time of near-trench magmatism indicates this extension continued until the triple junction migrated beneath the region.

The diffuse network of strike-slip and normal faults in south-central Alaska along which there was gold-quartz mineralization would be expected in the region above the slab window. Many of the mineralized faults in the Chichagof, Sitka, Port Valdez, Moose Pass, and Hope-Sunrise areas are dextral faults with orientations at a low angle to the regional strike of bedding and cleavage. They presumably were also at a low angle to the ancient continental margin, which suggests that despite the variability in kinematics between some areas (e.g., lower versus upper Kenai Peninsula), a number of areas of gold-quartz mineralization were affected by the same deformational regime, which had a component of dextral shear.

The younger, gouge-filled dextral faults also record a significant dextral component of the relative motion, consistent with inferred Kula–North America relative plate motions. We infer there must have been a greater dextral component of plate motion after triple junction passage. Pavlis and Sisson (1995), in their study of the Tana Glacier area, also found evidence for dextral-transpressional deformation in the region that would have been above the slab window. Both studies are consistent with inferred Kula–North America relative plate motions and rates, in which the Kula–North America relative velocity is north-northwest oriented and approximately double the Farallon–North America relative motion, which was north-northeasterly directed (Engebretson et al., 1985; Lonsdale, 1988). If it had been the Kula-Farallon triple junction that migrated from west to east beneath southern Alaska, the relative plate motions would have been much higher after passage of the triple junction, with an associated greater component of dextral shear—particularly along the southeastern Alaska margin.

Deformation and magmatism near transform segments would be markedly different from areas where ridge segments were consumed. We can assume that some transform segments were subducted beneath southern Alaska, which would have caused a pause and a jump in the locus of near-trench magmatism, a change in velocity and possibly a change in sense of margin parallel-shear, in addition to deformation caused by topography of the transform segment (Fig. 10). In the Woodlark Basin, where ridge subduction is occurring today, there is nearly 4 km of relief across transform offsets (Taylor and Exon, 1987).

If it was the Kula-Farallon ridge that was being subducted, plate reconstructions indicate most transform segments were right-stepping (e.g., Engebretson et al., 1985). We cannot link any particular sequence of structural events to this process, but along-strike changes in the sense of offset of mineralized faults with the same orientation (such as between Nuka Bay and Thunder Bay) could perhaps be due to this mechanism. Moreover, the effects of subducting a right-stepping transform segment would be markedly different from a left-stepping segment. Poole (1996) proposed subduction of a left-stepping transform segment and a resultant jump in the TRT triple junction to the west to account for slight variations in the trend of intrusive ages in the Sanak-Baranof belt.

Differences in the level of exhumation of the accretionary complex may have caused the variations in the observed structural response to ridge subduction. However, the *P-T* estimates from gold-quartz vein fluid inclusions (1.5 to 3.0 kbar; Goldfarb et al., 1986; Borden et al., 1992; Pickthorn, 1982; Dadoly, 1987) and from the Chugach metamorphic complex (~2.5 kbar; Sisson et al., 1989) are within the same broad range of crustal depths between about 5 and 10 km. Therefore, although they appear to have formed in the upper crust, it is beyond the resolution of the data to determine if there are real differences in amount of uplift between different regions. In the northern Kenai Peninsula, gold-quartz mineralized faults cut gouge-filled fault zones, and, as in all areas, the gold-quartz veins are cut by gouge-filled fault zones. Thus, there were approximately the same deformational conditions (*P* and *T*) both before and after ridge-subduction related gold mineralization.

Comparison with Other Ridge Subduction Events

We see a remarkable similarity in the pattern of seismicity and focal mechanisms between the Woodlark Basin, where ridge subduction is occurring today, and southern Alaska. In the Woodlark basin, away from the region where the ridge is being subducted, focal mechanisms indicate thrust faults parallel to the trench, as would be expected (Cooper and Taylor, 1987). However, in the region of ridge subduction, there are no thrust faults, only strike-slip faults and nearly vertical dip-slip faults. These focal mechanisms are almost identical to our finding of strike-slip and normal, but no reverse, mineralized faults that formed during ridge subduction in southern Alaska.

The Chile triple junction, the other location where ridge subduction is occurring today, may be more analogous to southern Alaska in early Tertiary time because the triple junction is migrating along the continental margin. Forsythe and Nelson (1985) found only strike-slip and normal faults in the region near the triple junction. These faults, like those in southern Alaska, also had different orientations in different regions. Despite the wide range of fault orientations between and within regions, they concluded the bulk of the data indicated regional E-W contraction—perpendicular to the margin. Kusky et al. (1997) also inferred margin perpendicular contraction for syn-ridge subduction faults in the Turnagain Arm area.

Hibbard and Karig (1990) studied probable effects of Miocene subduction of a backarc spreading center in the Shimanto accretionary complex of southwestern Japan. Direct evidence for ridge subduction is limited to a small area (~20 km^2) where they found a pervasive set of brittle faults that cut intrusives related to ridge subduction. They found thrust, strike-slip, and normal faults sets that are relatively homogenous and taken together

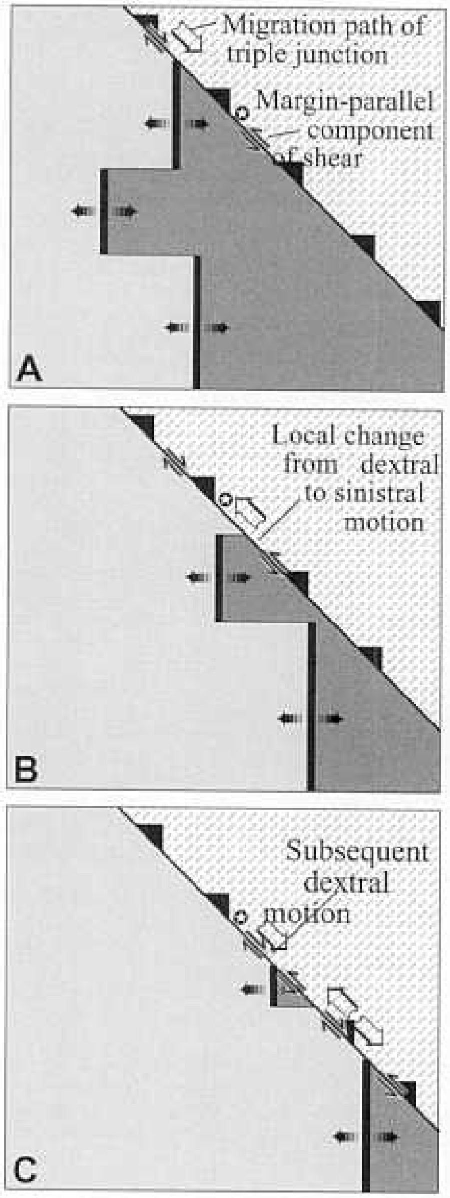


Figure 10. Hypothetical tectonic map showing how subduction of transform segments can cause jumps in the location of the trench-ridge-trench (TRT) triple junction. A: During subduction of a ridge segment, TRT triple junction is migrating to the southwest, and margin-parallel component of shear is opposite on either side of the ridge. B: During subduction of a transform segment, the triple junction becomes a trench-transform-trench triple junction and migrates to the northwest. C: Continued subduction of the transform leads to another ridge segment and and return to a southeast migrating TRT triple junction. Note how at the star (✪) the sense of shear along the continental margin (the overriding plate) changed from right-lateral, to left-lateral, and back to right lateral. This mechanism may explain some of the complexity in the record of brittle faulting in southern Alaska.

indicate contraction roughly perpendicular to the paleotrench. Again, this is similar to the relationships Kusky et al. (1997) found in the Turnagain Arm area of Alaska, with the exception of the presence of thrust faults. In Turnagain Arm, Kusky et al. (1997) concluded that thrust faults were early and were followed by normal and strike-slip faults. Perhaps the same relationship exists in Japan but was not noted.

Therefore, strike-slip and normal faulting above a slab window at the time of ridge subduction may be a common occurrence. If so, these faults may be related to deformation in the region above the slab window. Because both the forward and trailing oceanic plates are still moving apart at the margins of the slab window, we consider it likely the region above the slab window would experience extension. Thus, the brittle faults reflect deformation in the transfer zone above and between the subducting oceanic plates.

CONCLUSIONS

• There was widespread brittle deformation of the southern Alaska accretionary complex associated with Paleocene-Eocene triple junction migration.

• In southeastern Alaska, gold-quartz mineralization during ridge subduction occurred on margin-parallel dextral faults that effectively focussed fluid flow forming the largest deposits, whereas in south-central Alaska, mineralization occurred on a diffuse set of dextral and normal faults, not on reverse faults.

• The structural history of the southern Alaska accretionary complex is remarkably consistent from Kodiak Island to southeastern Alaska, and includes (1) underplating, offscraping, regional metamorphism, and shortening, (2) orogen-parallel extension that occurred prior to, and at the early stages of ridge subduction, (3) near-trench magmatism and locally regional high-*T*, low-*P* metamorphism, (4) lode-gold mineralization along strike-slip and/or normal faults, (5) right-lateral brittle faulting without fluid flow on margin-parallel faults, and (6) local vertical-axis rotations.

• Brittle deformation during ridge subduction and triple junction migration is related to the increasing influence of the forward subducting plate, the decreasing influence of the trailing plate, and the thermal pulse and decreased basal friction from the slab window. In addition, extensional deformation of the forearc will be caused by divergence of the subducting oceanic plates at the margins of the slab window.

• Additional factors make a detailed comparison of structures between regions in Alaska difficult. These include the timing and extent of oroclinal bending of southern Alaska, changes in plate motions, and subduction of transform segments with associated jumps in the locus of near-trench magmatism and changes in velocity and possibly sense-of-offset of margin parallel faults. The fundamental difference in the character of the fault sets between south-central and southeastern Alaska indicates there was some bend in the proto-Alaskan margin at the time of ridge subduction.

• Extensional and strike-slip faulting during ridge subduction in southern Alaska appears similar to brittle fault patterns near the Chile triple junction, and to the pattern of shallow earthquake focal mechanisms in the Woodlark basin, where ridge subduction is occurring today.

• Extensional and strike-slip faulting above a slab window may be a common occurrence during ridge subduction, reflecting deformation in a thermally weakened transfer zone above and between the subducting and still diverging oceanic plates.

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